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ENVIRONMENTAL HEAT TRANSFER TO A MICROCLIMATE COOLING SYSTEM DURING HEAT EXPOSURE

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Report No. 98-2

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BETHESDA, MARYLAND

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Technical Report 98-2, supported by the Naval Medical Research and Development Command, Department of the Navy, under Work Unit #62233N MM33P30.005-6207. The views expressed in this article are those of the authors and do not reflect the official policy or position of the Department of the Navy, Department of Defense, or the U.S. Government. Approved for public release, distributed unlimited.

Summary

Problem

A water-based microclimate cooling system (MCS) provides an avenue for heat loss when physical activity and protective clothing encapsulation are required in extreme heat. When the temperature of the water (T_w) circulated through the system is lower than mean skin temperature ($\bar{T}_{sk}$), heat from the body is transferred to the water. However, heat transfer to a water-based MCS can be derived not only from the body but also from the environment. When ambient temperature (T_a) is greater than T_w, heat transfers from the environment to the circulated water. In very hot environments, when T_a is much greater than $\bar{T}_{sk}$, heat transfer from the environment ($\dot{Q}_{env}$) is greater than heat transfer from the body ($\dot{Q}_{body}$). To reduce $\dot{Q}_{env}$, previous investigators have used insulating ensembles over the garment portion of the cooling system; however, it is uncertain to what extent these clothing ensembles reduce $\dot{Q}_{env}$, especially in very hot environments.

Objective

The purpose of this study was to evaluate $\dot{Q}_{env}$ to a water-based MCS under controlled environmental conditions. With the results of this study, heat transfer measured during physiological tests could be apportioned between $\dot{Q}_{env}$ and $\dot{Q}_{body}$.

Approach

The experiments were conducted in an environmental chamber controlled to maintain a hot, dry climate (T_a = 49°C; relative humidity = 20%). This climate was selected because subsequent physiological testing was to occur in these conditions. All tests were performed on a manikin composed primarily of rubber with very low thermal conductivity. The manikin was suspended in an upright position and outfitted with a water-based MCS and clothing layers to be used in future testing. Heat transfer to the MCS was measured at four temperatures of water, 15 to 30°C in 5°C increments. The range of T_w was selected to encompass that expected to be used in future studies. $\dot{Q}_{env}$ data were plotted with (T_a - T_w) and with the temperature of the clothing layer adjacent to the MCS suit (T_{lyr1} - T_w), and curves were fit to the data. A first-order equation fit was determined to be "good" when there was a significant linear relationship between the

variables with $p < .001$, the coefficient of determination (R^2) was greater than .80, and the 99% confidence interval (CI) for the slope of the line (β_1) did not include zero.

Results

The linear model fit to the data for $\dot{Q}_{env}$ with ($T_a - T_w$), using data from the entire 60 min of testing, produced a prediction equation that had a significant linear relationship ($r = 0.4$, $p < .001$), with a small coefficient of determination ($R^2 = 0.2$). A significant linear relationship was found ($r = 0.95$, $p < .001$) with a larger R^2 (0.89) when excluding the data collected during the first 20 min of the tests when the system was not in or approaching steady state. The 99% CI for β_1 was 3.3 to 4.3 $w \cdot {}^\circ C^{-1}$ and did not include zero. Alternative predictor variables were sought that would produce a good model not requiring the system to be in or approaching steady state utilizing the data collected over the entire 60 min of the tests. A second prediction equation was derived for $\dot{Q}_{env}$ when T_w and T_{lyr1} were known ($\dot{Q}_{env} = 7 \cdot [T_{lyr1} - T_w] + 5.5$). A significant linear relationship was found ($r = 0.99$, $p < .001$), with a large R^2 (0.97) and a 99% CI for β_1 (6.7 to 7.3 $w \cdot {}^\circ C^{-1}$) that did not include zero. The prediction equation for total $\dot{Q}_{env}$, expressed as heat transfer per length of tubing ($[7 \cdot (T_{lyr1} - T_w) + 5.5] \cdot \text{total length of tubing}^{-1} \cdot \text{regional length of tubing}^{-1}$) underpredicted $\dot{Q}_{env}$ for some regions (e.g., gluteus and calves) and overpredicted $\dot{Q}_{env}$ for other regions (e.g., arm). Different prediction equations for each region were determined because of the differences in regional contribution to $\dot{Q}_{env}$.

Conclusions

$\dot{Q}_{env}$ increased in direct proportion to the difference between T_w and T_{lyr1}. The insulating clothing reduced $\dot{Q}_{env}$ because T_{lyr1} was 7 to 13 °C lower than T_a after 60 min of testing. However $\dot{Q}_{env}$ was substantial, equivalent to metabolic heat production during light work (Åstrand & Rodahl, 1977), even when the tube suit was covered by insulating clothing. $\dot{Q}_{env}$ under the conditions of this study may account for upward of 20% of heat transfer to an MCS when heavy work is performed (Canine et al., 1997). Because many MCSs have limited cooling capacities, it is important to reduce $\dot{Q}_{env}$. Thus, it is advantageous to wear heavy insulating garments in hot environments when microclimate cooling is used. Good linear models were found for predicting $\dot{Q}_{env}$ when T_a and T_w are known. By using these models, heat transfer measured during future physiological tests can be apportioned between $\dot{Q}_{env}$ and $\dot{Q}_{body}$.

Introduction

Heat stress and the resultant heat strain can adversely affect the ability of military personnel to perform work tasks and combat missions. In low-humidity environments, where ambient temperature (T_a) exceeds mean skin temperature ($\bar{T}_{sk}$), the primary avenue for heat loss is sweat evaporation. In hot environments where evaporation is limited, body heat gain progresses quickly (Ohnaka et al., 1993; Taylor & Orlansky, 1993; Tilley et al., 1987; White & Hodous, 1987). Thus, it is prudent to institute countermeasures to heat stress when work is required in environments where heat dissipation is limited. One countermeasure for such environments is a water-based microclimate cooling system (MCS).

Water-based MCSs consist of a tight-fitting garment onto which tubing is sewn, a fluid reservoir, and a fluid cooling source (Pimental et al., 1988; Webb et al., 1972). Fluid in the reservoir is cooled, pumped through the tubing in the garment, and then returned to the reservoir in a closed-circuit system. The water-based MCS provides an avenue for body heat loss when physical activity and clothing encapsulation are required in high-heat environments.

When the temperature of the water (T_w) circulated through the tubing is lower than $\bar{T}_{sk}$, heat is conducted from the body to the water. The heat transfer from the body to the circulated water ($\dot{Q}_{body}$), determined by the principals of thermodynamics, is proportional to the temperature difference between $\bar{T}_{sk}$ and T_w and to the surface area across which heat is being transferred. This relationship is defined by the following equation (Halliday & Resnick, 1988):

$$\dot{Q}_{body} = \kappa \cdot L^{-1} \cdot A_{sk} \cdot (\bar{T}_{sk} - T_w)$$

where $\dot{Q}_{body}$ = conductive heat transfer in watts (w), κ = thermal conductivity of the tubing ($w \cdot {}^\circ C^{-1} \cdot cm^{-1}$), A_{sk}= cross-sectional area of the tubing in contact with the skin (cm^2), and L = thickness of the tubing wall (cm).

Heat transfer to a water-based MCS is derived not only from the body but also from the environment. The surface area of the tubing in the garment not in direct contact with the skin is in contact with the environment (A_{env}). When T_a is greater than T_w, heat is transferred from the environment to the circulated water. Heat transfer between the environment and the water is proportional to the difference between T_w and T_a. Thus, total heat transfer ($\dot{Q}_{tot}$) to a water-based MCS can be described as:

$$\dot{Q}_{tot} = \kappa \cdot L^{-1} \cdot \left[[A_{sk} \cdot (\bar{T}_{sk} - T_w)] + [A_{env} \cdot (T_a - T_w)] \right]$$

In environments, where T_a is equal to $\bar{T}_{sk}$, heat transfer from the environment is greater than heat transfer from the body because A_{env} is much greater than A_{sk} due to the cylindrical shape of the tubing. In very hot environments, when T_a is much greater than $\bar{T}_{sk}$, $\dot{Q}_{env}$ could be greater than $\dot{Q}_{body}$; thus, attributing all of $\dot{Q}_{tot}$ to $\dot{Q}_{body}$ would be erroneous.

In previous studies, investigators have used insulating ensembles over the MCS to reduce $\dot{Q}_{env}$ (Hambraeus et al., 1994; Shvartz & Benor, 1971; Webb & Annis, 1968). However, it is uncertain to what extent these clothing ensembles restrict $\dot{Q}_{env}$. In this study, $\dot{Q}_{tot}$ was measured with an MCS placed on a manikin with a surface temperature equal to T_w in the MCS. The data were modeled to identify variables that could serve as predictors of $\dot{Q}_{env}$. The intent was to use this model in future physiological tests, thereby enabling apportionment of total heat transfer between $\dot{Q}_{env}$ and $\dot{Q}_{body}$.

Methods

The experiments were conducted in an environmental chamber controlled to maintain a hot, dry condition (T_a = 49°C; relative humidity = 20%). This climate was selected because subsequent physiological testing was to occur under these conditions. All tests were performed on a manikin composed primarily of rubber with low thermal conductivity. An MCS was used, consisting of a tube garment, a water chiller, flow control, and temperature instrumentation, to measure $\dot{Q}_{env}$. Heat transfer from the environment was measured at each of four temperatures of water in the MCS; the range of T_w tested, 15 to 30°C, was selected to encompass the range to be used in future studies.

Test Procedures

The manikin was suspended in an upright position and outfitted with shorts, socks and shoes, the tube garment, cotton coveralls, and Saratoga® chemical protective (CP) clothing. The CP ensemble consisted of a hooded jacket, bibbed trousers, butyl rubber gloves and boots, a chemical protective mask, and a rubber hood worn over the mask.

After being clothed, the manikin was placed in a chamber for a minimum of 16 hr. T_a during the equilibration phase was maintained at either 15, 20, 25, or 30°C and matched the

temperature of water in the MCS. The surface temperature of the manikin was measured with thermistors (409B, Yellow Springs Instruments; Yellow Springs, OH). The thermistors were placed on the left side of the manikin at the foot, calf, thigh, abdomen, forearm, scapula, and cheek. One-minute averages of site temperatures were recorded on a calibrated data logger (Science Electronics; Dayton, OH). Mean surface temperature of the manikin ($\bar{T}_{man}$) was calculated using the formula of Hardy & DuBois (1938): $(0.07 \cdot T_{cheek}) + (0.175 \cdot T_{scapula}) + (0.175 \cdot T_{abdomen}) + (0.14 \cdot T_{forearm}) + (0.05 \cdot T_{hand}) + (0.19 \cdot T_{thigh}) + (0.13 \cdot T_{calf}) + (0.07 \cdot T_{foot})$

Once surface temperature stabilized and equilibrated with the chamber temperature, water circulation through the MCS commenced. T_w in the MCS was set to match the manikin surface temperature. At this time, $\bar{T}_{man}$, T_w, and T_a were matched at either 15, 20, 25, or 30°C. In this condition, heat transfer to or from the MCS was minimal. The null $\dot{Q}$ condition (i.e., $\dot{Q}_{env} \approx 0$ w) was recorded for 20 min and verified. Once a null baseline was established, the manikin was moved from the equilibration chamber to the test chamber that was maintained at 49°C and 20% relative humidity. In the test chamber, $\dot{Q}_{env}$ was measured for 60 min.

Microclimate Cooling System

Each of the MCS components is described separately as follows:

Tube Garment – The tube garment (Diving Unlimited International; San Diego, CA) was constructed of an elastic, nylon material. The suit covered the body surface, except the face, feet, and hands. Woven through the nylon material was polyvinyl chloride tubing (Tygon®, Performance Plastics; Akron, OH), with inner diameter of 1.6 mm and outer diameter of 3.2 mm, through which water was circulated. The water delivered from the chiller was divided into six parallel circuits, one each for the following six regions: head/neck, arms, torso, gluteus, thighs, and calves. In each of the regions, the water was diverted to 12 parallel circuits of the small diameter tubing. Although the number of parallel circuits was constant across the regions, the length of tubing in each region was different. The distribution of the tubing is listed by region in Table 1.

Table 1 – Length and percentage of total length of small diameter tubing in each region.

Region	Length of Tubing (cm)	Percentage of Tubing (%)
Head	1661.2	10.6
Torso	2355.9	15.0
Gluteal	2194.6	14.0
Arms	2839.7	18.0
Thighs	2895.6	18.4
Calves	3779.5	24.0
Total	**15726.6**	**100.0**

Water Chiller – The water source was a chiller fitted with an immersion cooling probe (Model HX150, Neslab Instruments; Portsmouth, NH). The chiller's 36 L reservoir and cooling capacity of 2000 w was sufficient to maintain T_w within a narrow range. The common temperature-controlled source provided water at the same T_w and flow rate to all six regions to the tube garment.

Flow Control – The water pumped from the chiller was diverted to six restriction valves that were used to achieve equal flow rates to the six regions. The restriction valves were set to allow a flow rate of 0.6 $L \cdot min^{-1}$ to each region, as measured by flow meters. The flow to each region was measured with sensitive turbine meters (E.G.&G Flow Technology; Phoenix, AZ). The flow meters were calibrated at the manufacturer, and accuracy was tested in our laboratory by collecting and weighting the water flowing through the valve over 10-min intervals. Using this technique, the flow meters were determined to be accurate within ± 0.1% at a flow rate of 0.6 $L \cdot min^{-1}$.

Instrumentation – T_w, as it arrived (T_{wi}) and as it exited the tube suit (T_{wo}), was measured with precision thermistors accurate to ± 0.002°C (Model No. SP034-47; Yellow Springs Instruments, Inc; Yellow Springs, OH). The thermistors were calibrated at the factory by measuring and recording the resistance in the thermistors while immersed in a standard oil bath at 0, 25, and 40°C. A resistance-temperature curve was derived using an equation for nonideal semiconductors (Steinhardt & Hart, 1968). Three additional thermistors (YSI 409B; Yellow Springs, OH) were used to measure temperatures at chest level between the clothing layers. Air temperature was measured between the tube garment and cotton coveralls (T_{lyr1}), between the

coveralls and the chemical protective clothing (T_{lyr2}), and on the exterior of the chemical protective clothing (T_a).

The resistance values from the thermistors measuring T_a, T_{lyr1}, and T_{lyr2} were read by a computer-controlled voltohmeter (PREMA 5000; Monclair, CA). The resistance values for the water flow, six inlet, and six outlet water temperature thermistors also were read by a voltohmeter (PREMA DMM 6047; Montclair, CA). Resistance values from thermistors and flow meters were sampled six times each minute and the values recorded as a 2-min mean.

Calculations – To calculate heat transfer to the MCS, the following equation was used:

$$\text{Regional } \dot{Q}_{env} = \text{regional } \dot{m}_w \cdot c_w \cdot \text{regional } \Delta T$$

where regional $\dot{Q}_{env}$ = heat transfer to the MCS by region, regional $\dot{m}_w$ = mass flow of water to the region, c_w = heat capacity of water, and regional ΔT = change in water temperature as it passed through the region ($T_{wo} - T_{wi}$). A sum of heat transfers from the six regions defined total environmental heat transfer (total $\dot{Q}_{env}$). All calculations of $\dot{Q}_{env}$ were performed by a GW-BASIC computer program (Webb Associates; Yellow Springs, OH).

Statistics

An SPSS-X computer program (SPSS, Inc.; Chicago, IL) was used to plot $\dot{Q}_{env}$ data against ($T_a - T_w$) data and against ($T_{lyr1} - T_w$) data, fit curves to the data, and plot the residual differences. A first-order equation fit was selected for the data because the law of thermodynamics describes the rate of heat transfer as a linear function. An equation was determined to be a "good" predictive model when the linear relationship between the variables was significant at $p < .001$, when the coefficient of determination (R^2) was greater than 0.80, and when the 99% confidence interval (CI) for the slope of the line (β_1) did not include zero. The chi-square technique was used to determine the odds that distributions differed by chance alone.

Results and Discussion

The results from the tests at 15, 20, 25, and 30°C, are presented in Tables 2 through 8.

Table 2 – T_{wi}, $\bar{T}_{man}$, T_{lyr1}, and $\dot{Q}_{tot}$ during whole-body cooling.

Temp (°C)	Time (min)	T_{wi} (°C)	$\bar{T}_{man}$ (°C)	T_{lyr1} (°C)	Total $\dot{Q}_{env}$ (w)
15	**0**	15.9	16.0	15.1	-1.5
	10	16.0	18.3	27.7	96.5
	30	16.1	19.2	33.4	127.4
	60	15.9	19.5	35.6	140.7
20	**0**	20.3	19.9	20.8	-3.3
	10	20.3	21.3	28.8	64.5
	30	20.4	22.4	33.7	93.9
	60	20.4	22.7	36.4	104.6
25	**0**	25.1	25.0	26.0	3.4
	10	25.1	26.5	32.6	69.6
	30	25.2	27.2	36.9	87.6
	60	25.2	27.4	38.6	95.3
30	**0**	30.4	30.4	29.3	-2.8
	10	30.4	31.6	35.5	54.4
	30	30.4	32.2	39.7	72.6
	60	30.4	32.4	41.5	78.7

Table 3 – Heat transfer (w) at the head during whole-body cooling.

Time	**15°C**	**20°C**	**25°C**	**30°C**
Min 0	1.4	2.5	2.0	1.3
Min 10	11.9	8.8	8.5	7.3
Min 30	15.3	11.1	10.1	9.2
Min 60	16.6	12.2	11.0	9.9

Table 4 – Heat transfer (w) at the arms during whole-body cooling.

Time	15°C	20°C	25°C	30°C
Min 0	-1.4	2.6	0.6	-1.3
Min 10	21.2	16.7	15.1	11.3
Min 30	26.2	19.8	17.6	14.0
Min 60	29.0	21.7	19.0	15.4

Table 5 – Heat transfer (w) at the torso during whole-body cooling.

Time	15°C	20°C	25°C	30°C
Min 0	0.9	1.4	0.5	-0.4
Min 10	15.8	11.8	10.9	8.0
Min 30	20.6	15.1	13.7	10.8
Min 60	22.6	16.7	14.9	11.5

Table 6 – Heat transfer (w) at the gluteus during whole-body cooling.

Time	15°C	20°C	25°C	30°C
Min 0	0.5	-0.4	-0.1	-0.5
Min 10	11.8	8.1	8.3	6.4
Min 30	15.7	11.3	10.9	8.8
Min 60	17.5	12.4	11.9	9.7

Table 7 – Heat transfer (w) at the thighs during whole-body cooling.

Time	15°C	20°C	25°C	30°C
Min 0	-0.3	1.0	0.2	-0.5
Min 10	19.2	13.4	13.5	11.2
Min 30	24.2	17.3	19.0	14.2
Min 60	26.2	19.2	21.1	15.0

Table 8 – Heat transfer (w) at the calves during whole-body cooling.

Time	15°C	20°C	25°C	30°C
Min 0	–2.5	0.3	0.2	–1.4
Min 10	16.5	12.9	13.5	10.2
Min 30	25.4	19.3	19.0	15.6
Min 60	28.7	22.4	21.1	17.2

With T_a held constant, we found that $\dot{Q}_{env}$ was greatest with the lowest T_w and $\bar{T}_{man}$. This was expected because heat transfer, as determined by the principles of thermodynamics, is proportional to the temperature difference between the objects across which heat is being transferred. These results show that $\dot{Q}_{env}$ was substantial, equivalent to metabolic heat production during light work (Åstrand & Rodahl, 1977), even when the MCS was insulated by clothing.

Models Derived

Prediction of $\dot{Q}_{env}$ Based on (T_a – T_w) - The data were modeled to identify variables that could serve as predictors of $\dot{Q}_{env}$. The intent was to use this model in future physiological tests, thereby enabling apportionment of total heat transfer between $\dot{Q}_{env}$ and $\dot{Q}_{body}$. $\dot{Q}_{env}$ data were plotted against (T_a – T_w), from minute 0 to minute 60 for each of the four conditions (138 data points), and a first-order curve was fit (see Figure 1). The first-order fit had the following statistical results: $r = 0.4$, $R^2 = 0.2$, $p < .001$, and SE = 35.6 w.

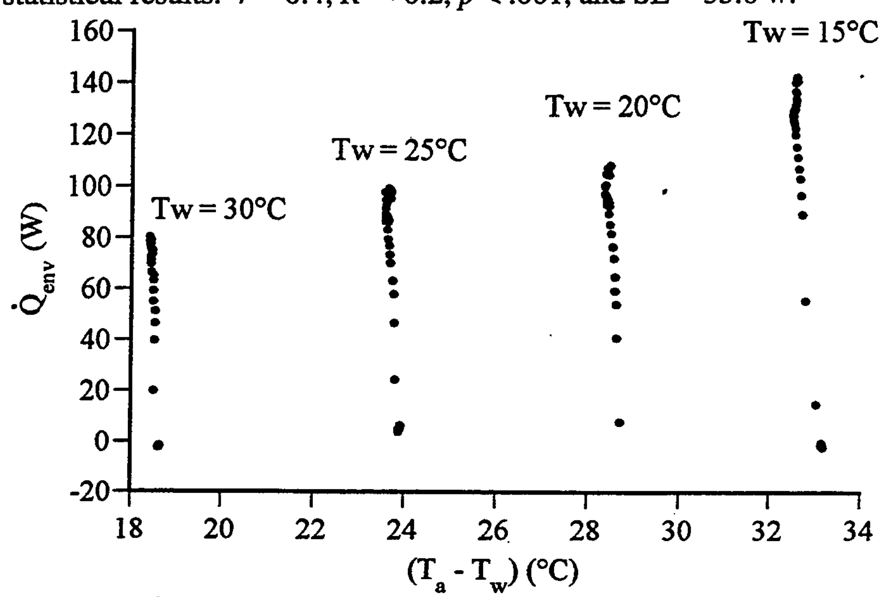

Figure 1 – $\dot{Q}_{env}$ with (T_a – T_w) using data from the four tests.

A β_1 of 1.0 and an R^2 of 1.0 would be expected in a system free of measurement error. Although this was not seen, the difference between expected and actual results was not due entirely to measurement error. When the manikin was transferred from the equilibration chamber to the test chamber, steady state was disturbed and large changes occurred in measured variables (see Figure 2).

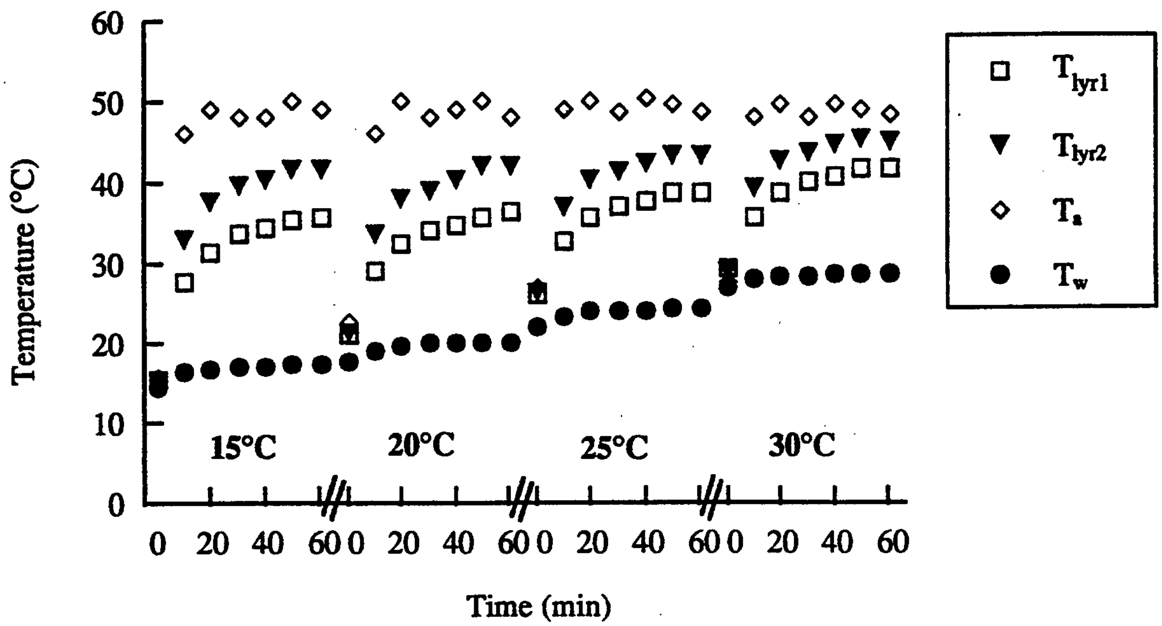

Figure 2 – T_{lyr1}, T_{lyr2}, T_a, and T_w over time.

T_{lyr1} and T_{lyr2} increased over the first 20 min, and the increase in heat exposure to the garment resulted in an increasing $\dot{Q}_{env}$ over time. While $\dot{Q}_{env}$ increased over time, $(T_a - T_w)$ did not change substantially over time (see Figure 2). To eliminate the influence of the dynamics during the initial change in $\dot{Q}_{env}$ on the overall curve.of best fit, data collected during the first 20 min of heat exposure were eliminated. Then the relationship of $\dot{Q}_{env}$ and $(T_a - T_w)$ was replotted using only 78 of the 138 data points (see Figure 3). A first-order fit of the data yielded an intercept (SE) of 1.8 w (4.0 w) and a β_1 (SE) of 3.8 w·°C^{-1} (0.2 w·°C^{-1}). The correlation coefficient for the fit was 0.95 and $R^2 = 0.89$. The two-tailed significance was $p < .001$ and the 99% CI was 3.3 to 4.3 w · °C^{-1}.

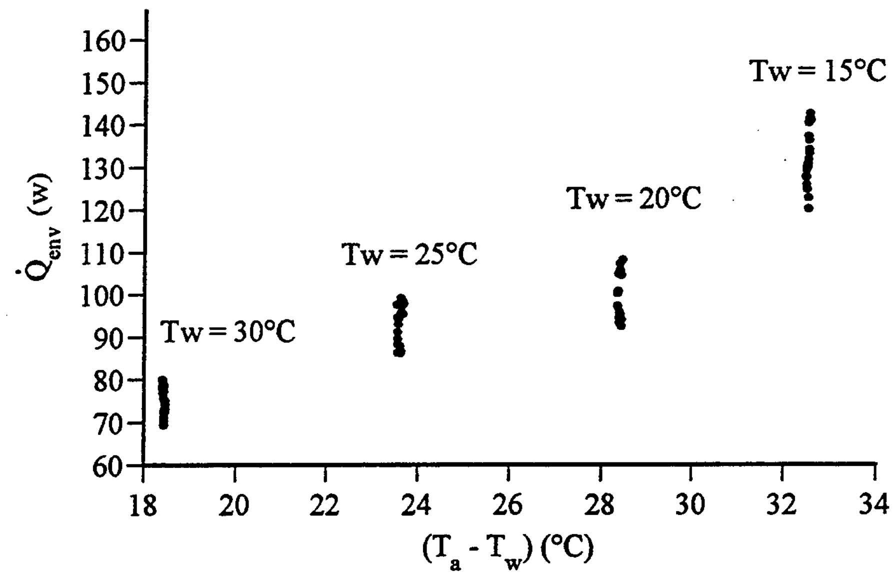

Figure 3 – $\dot{Q}_{env}$ plotted against $(T_a - T_w)$ over time using data from minute 20 to minute 60.

This model was a better predictor of $\dot{Q}_{env}$; however, a problem arose in using the model to calculate the environmental contribution to $\dot{Q}_{tot}$ for physiological studies. This model can be used only when the system is in or approaching steady state. Thus, for data collected during periods when transitory changes occur in $\dot{Q}_{env}$, as at the start of a heat exposure, $\dot{Q}_{env}$ cannot be estimated accurately using this model.

Prediction of $\dot{Q}_{env}$ Based on $(T_{lyr1} - T_w)$ - To determine if the steady-state requirement could be avoided, the relationship between $\dot{Q}_{env}$ and a second variable was examined. $\dot{Q}_{env}$ was plotted against $(T_{lyr1} - T_w)$ utilizing data from minute 0 to minute 60 of the tests (138 data points) (see Figure 4). A first-order fit of the data yielded an intercept (SE) of 5.5 w (1.2 w) and a β_1 (SE) of 7.0 w·°C^{-1} (0.1 w·°C^{-1}). The r for the fit was 0.99 and the R^2 was 0.97, with a two-tailed significance of $p < .001$ and 99% CI of 6.7 to 7.3 w·°C^{-1}.

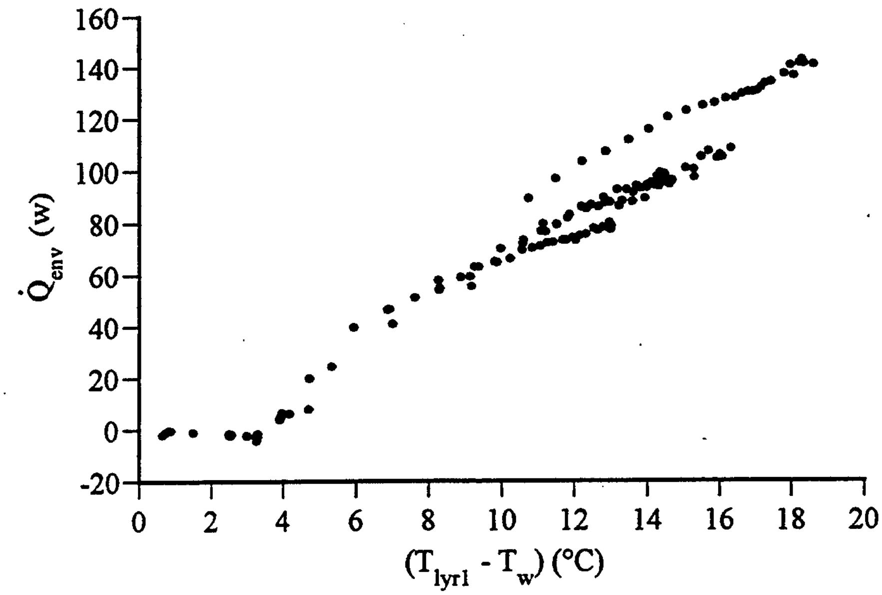

Figure 4 - $\dot{Q}_{env}$ plotted against $(T_{lyr1} - T_w)$ over time using data from minute 0 to minute 60.

Plots of the residual differences between actual and predicted $\dot{Q}_{env}$ with actual $\dot{Q}_{env}$ are graphically displayed in Figure 5. The residual plots were examined to determine if the residuals were symmetric about zero at all levels of actual $\dot{Q}_{env}$, that there were proportionally more residuals with small absolute values than with large absolute values, and that there were no outlying data points. The residuals were plotted with the four T_w categories to check for normality, variance homogeneity, and absence of outliers (see Figure 6).

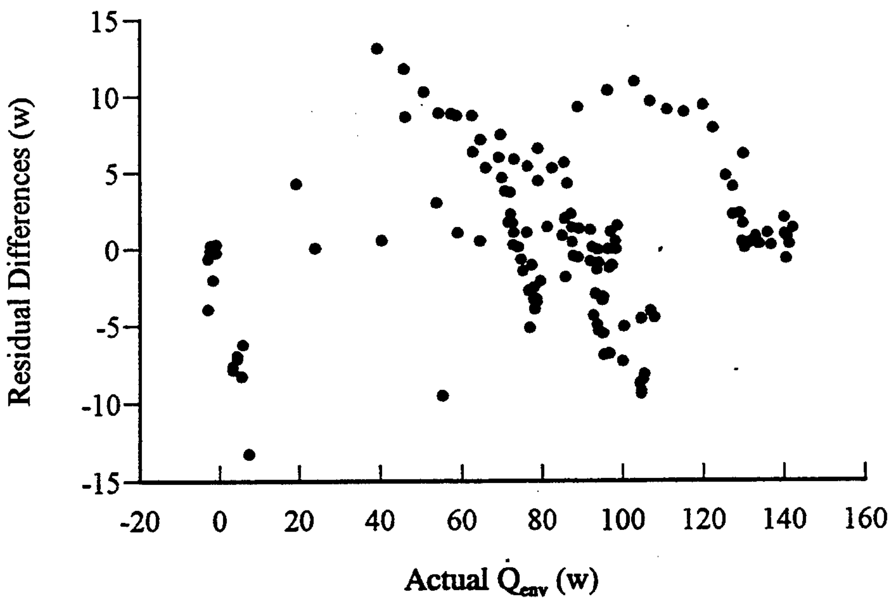

Figure 5 - Residual differences between actual and predicted $\dot{Q}_{env}$ with actual $\dot{Q}_{env}$.

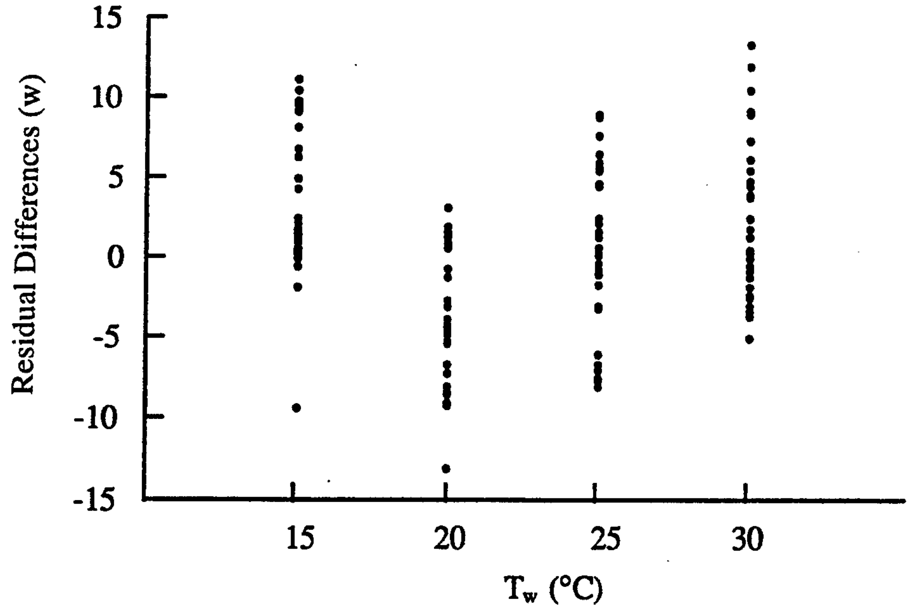

Figure 6 – Residual differences between actual and predicted $\dot{Q}_{env}$ with water temperature.

Prediction of Regional $\dot{Q}_{env}$ Based on (T_{lyr1} – T_w) - This study was conducted as part of a larger program including physiological testing. The aim of the program is to determine heat transfer from various body regions during different modes of exercise. To better understand regional contributions to $\dot{Q}_{env}$, environmental heat transfer for each of six regions of the MCS was examined. Since T_a, T_w, and κ were not different among regions, it was expected that differences in regional $\dot{Q}_{env}$ would be related to the area of tubing in contact with the environment and that differences in tubing length in a region would account for most of the differences in regional $\dot{Q}_{env}$. The finding that contribution percentage of regional $\dot{Q}_{env}$ to total $\dot{Q}_{env}$ is equivalent to percentage of total length of tubing in a tube suit has been reported previously (Fonesca, 1976). In this study, the contribution percentage of regional $\dot{Q}_{env}$ to total $\dot{Q}_{env}$ was different from the percentage of total tubing in the region (see Figure 7). A chi-square test revealed a significant difference ($p < 0.05$) between contribution percentage of regional $\dot{Q}_{env}$ to total $\dot{Q}_{env}$ and percentage of regional tubing length to total tubing length.

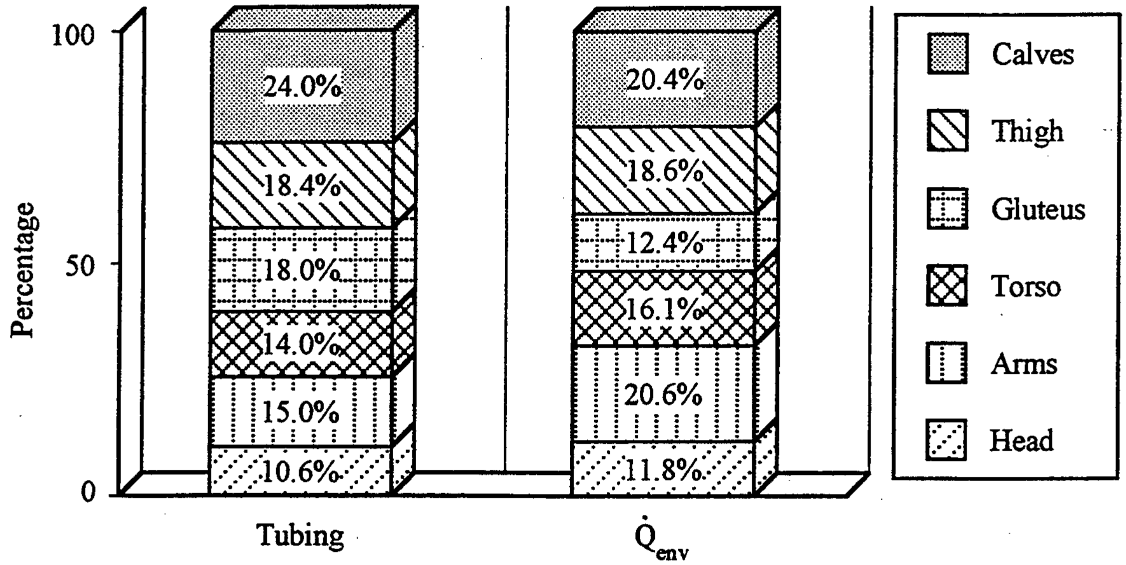

Figure 7 – Regional percentages of tubing length and $\dot{Q}_{env}$.

The prediction equation for total $\dot{Q}_{env}$, expressed as heat transfer per length of tubing ([7 · (T_{lyr1} − T_w) + 5.5] · total length of tubing^{-1} · regional length of tubing^{-1}), was not a particularly good predictor of regional $\dot{Q}_{env}$. Residual plots revealed that for some of the regions the residual differences were entirely positive and for others the residual differences were primarily negative. Thus, the prediction equation underestimated $\dot{Q}_{env}$ for some regions (e.g., gluteus and calves) and overestimated $\dot{Q}_{env}$ for others (e.g., arms). It appears that heat transfer was lower than expected in areas that were more insulated from the environment; the calves had an additional layer provided by the rubber boots and the gluteal region was covered by both the CP trousers and jacket. Prediction equations for regional $\dot{Q}_{env}$ were determined separately because of the differences in regional contribution to $\dot{Q}_{env}$ (see Table 9).

Table 9 – Prediction equations for regional $\dot{Q}_{env}$.

Region	***r***	***R^2***	**99%CI ($w \cdot °C^{-1}$)**	**β_1 (SE) ($w \cdot °C^{-1}$)**	**Intercept (SE) (°C)**
Head	.98	.96	0.71 to 0.77	0.74 (0.01)	2.02 (0.14)
Arms	.98	.96	1.54 to 1.38	1.46 (0.03)	1.04 (0.31)
Torso	.99	.97	1.56 to 0.68	1.12 (0.17)	0.80 (0.20)
Gluteal	.98	.97	0.91 to 0.85	0.88 (0.01)	0.35 (0.16)
Thighs	.98	.96	1.36 to 1.26	1.31 (0.02)	1.30 (0.28)
Calves	.98	.96	1.60 to 1.44	1.52 (0.03)	−0.01 (0.30)

Although the equations derived here can be used to predict $\dot{Q}_{env}$, these equations may only be applicable when this particular MCS, clothing ensemble, and environmental condition are employed. During physiological tests, physical activity will increase air flow within and outside the clothing ensemble. The enhanced air exchange may alter heat transfer through the clothing layers and affect prediction of $\dot{Q}_{env}$ based on $(T_a - T_w)$. In addition, because the study took place in a dry environment using a manikin, it is uncertain how the presence of water vapor in the ensemble would affect heat transfer to the MCS.

Conclusions

A significant linear relationship was found between $\dot{Q}_{env}$ and $(T_a - T_w)$ if data collected during the initial 20 min of testing were excluded. A significant linear relationship was found between $\dot{Q}_{env}$ and $(T_{lyr1} - T_w)$, even when the initial 20 min of data were included. Prediction equations for each regional $\dot{Q}_{env}$ were determined, and significant linear relationships were found between $\dot{Q}_{env}$ and $(T_{lyr1} - T_w)$ for each region. During future physiological tests, heat transfer can be apportioned between $\dot{Q}_{env}$ and $\dot{Q}_{body}$ by using these models. $\dot{Q}_{env}$ increased in direct proportion to the difference between T_w and T_{lyr1}. The insulating clothing reduced $\dot{Q}_{env}$ because T_{lyr1} remained lower than T_a throughout the 60-min test. However even when the tube suit was covered by insulating clothing, $\dot{Q}_{env}$ was equivalent to metabolic heat production during light-to-moderate work (Åstrand & Rodahl, 1977). Because many MCSs have limited cooling capacities, it is imperative to reduce $\dot{Q}_{env}$. Thus, it is advantageous to wear heavy insulating garments in hot environments when microclimate cooling is used.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
2 February 98

3. REPORT TYPE AND DATE COVERED
Final 1997

4. TITLE AND SUBTITLE
Environmental heat Transfer to a Microclimate Cooling System During Heat Exposure

5. FUNDING NUMBERS
Program Element: 62233N
Work Unit Number:
M33P30.005-6207

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION
Report No.
98-2

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Medical Research and Development Command
National Naval Medical Center
Building 1, Tower 2
Bethesda, MD 20889-5044

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE
A

13. ABSTRACT *(Maximum 200 words)*

Heat transfer from the environment ($\dot{Q}_{env}$) to a water-based microclimate cooling system (MCS), operated at four temperatures of water (T_w), was measured utilizing a rubber manikin outfitted in coveralls and chemical protective clothing. $\dot{Q}_{env}$ increased in direct proportion to the difference in T_w and ambient temperature (T_a). Good linear models were found for predicting $\dot{Q}_{env}$ when T_a or temperature between clothing layers and T_w are known. These models can be used in future physiological tests to apportion heat transfer between the environment and the body. $\dot{Q}_{env}$ was substantial, greater than 100 w at the lowest temperature of water, even when insulated from the environment. Because many MCSs have limited cooling capacities, it is important to reduce $\dot{Q}_{env}$. Thus, it is advantageous to wear insulating garments in hot environments when microclimate cooling is used.

14. SUBJECT TERMS
heat transfer, microclimate cooling system, environmental heat transfer, water-based microclimate cooling system,

15. NUMBER OF PAGES
20

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited